An Investigation of the Role of Nutrient Gradients in the Episodic Formation, Maintenance and Decay of Thin Plankton Layers in Coastal Waters

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LONG-TERM GOALS

Thin plankton layers are patches of phytoplankton and/or zooplankton that range in thickness from a few centimeters to a few meters yet can extend horizontally for kilometers and persist for days. Recent work has shown that thin layers can be sufficiently intense and persistent to affect the performance of current and planned Navy optical and acoustical sensors. In Hanson and Donaghay (1998) we showed how thin plankton layers are often embedded within steep nutrient gradients or associated with transient chemical plumes. The presence of thin plankton layers was also shown to have a profound influence on chemical distributions and chemical and biological rate processes within the water column. However little is known about the mechanistic roles that fine-scale chemical gradients play in the episodic formation and maintenance of productive, thin plankton layers in coastal waters. What are the critical temporal and spatial scales for the interaction of chemical gradients and such plankton patchiness? To explore these questions we are investigating the following two hypotheses:

1. Episodic variability in nutrient gradients, driven by and coupled to dynamic meteorological and physical mixing processes, is critically important to the development, persistence and behavior of thin plankton layers in coastal waters.

2. Thin plankton layers exert a substantial influence on the fine-scale distribution of dissolved chemicals and on their biologically mediated reaction rates within coastal waters.

During the past ten years we have been developing, improving and testing submersible chemical analyzers and novel cables and autonomous deployment technologies for coastal monitoring (Hanson and Donaghay, 1998; Hanson and Moore, 2001). In addition to being commercially available, these new chemical sensing technologies are <u>now</u> sufficiently advanced to successfully make high-resolution measurements of biological, physical <u>and chemical</u> data on comparable scales. This technological capability is required to elucidate the combined and relative roles of chemical, physical and biological processes in the dynamics of thin plankton layers and to further develop and test a predictive model (Donaghay and Osborn, 1997) for thin plankton layer formation, maintenance and decay in coastal waters.

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OBJECTIVES

The objectives for this three-year project (1 Feb. 2004 - 31 Jan. 2007) are to increase our understanding of the chemical processes and mechanisms influencing the dynamics and impacts of thin plankton layers in the coastal ocean. The “chemical” scientific objectives primarily involve conducting time-series investigations of the fine scale vertical nutrient gradients associated with vertically thin, horizontal layers of plankton. Accomplishing these objectives will require close collaboration with other ONR LOCO researchers.

1. To participate in thin layers field studies at coastal sites (Monterey Bay CA in August 2005) selected by the ONR program on Layered Organization in the Coastal Ocean (LOCO).
2. To monitor the variability in fine-scale nutrient distributions, in both the vertical (primary effort) and horizontal (limited effort) dimensions at the site for time periods of 1 to 4 weeks.
3. To document and evaluate the influence of variations in steep nutrient gradients and chemical plumes, attributed to episodic physical and biological events, on the biological and optical properties of thin plankton layers.
4. To document and investigate the influence of biological (i.e. thin plankton layers) and physical processes (i.e. storms, currents, upwelling, turbulence) on nutrient distributions at the coastal study site.
5. To determine the source of the nutrient gradients or plumes found to be associated with thin plankton layers.

With the completion of the two year field monitoring program the primary objectives are now to carefully process and analyze all of the nutrient data so that it can be used to answer these important scientific questions (3-5) and to prepare publications on the results.

APPROACH

The primary operational effort for SubChem Systems to meet these objectives involved monitoring the temporal fine-scale variability in vertical nutrient distributions. A secondary effort utilized comparable submersible chemical analyzers (both ship and AUV deployed) to document horizontal and vertical variability in the immediate region of the moored array. We utilized a new class of submersible chemical analyzers that have been specifically developed for determining and monitoring the fine-scale variability of nutrients in coastal waters. The four types of submersible chemical analyzers listed in Table 1 were used in the LOCO field work. These analyzers can be selectively configured to continuously and simultaneously measure a variety of dissolved inorganic nutrients: nitrate, nitrite, ammonium, phosphate, silicate, iron(II) and iron(III).

Table 1. Commercially available submersible chemical analyzers from SubChem Systems, Inc. These analyzers can be selectively configured to continuously and simultaneously measure the following dissolved inorganic nutrients nitrite, nitrate, phosphate, silicate, ammonium and iron.

SubChem Analyzers	# Channels	Cabled or Remote	Deployment modes & platforms
SubChemPak Analyzer	4-8	cabled	Vertical and towed profilers
Autonomous Profiling Nutrient Analyzer (APNA I and II)	4	both	ORCAS Array IOPC profiler Vertical and towed profilers
MARCHEM Analyzer	4	remote	REMUS AUV

These submersible chemical analyzers were deployed from three different platforms at various times during these experiments.

1. **Extended Deployment of an Autonomous Profiling Nutrient Analyzer (APNA) on URIs ORCAS IOPC Profiler**. The bottom-up IOPC profiler, developed during 1999-2001 with NOPP funding (URI, WET Labs, Inc. and SubChem Systems, Inc.), was out-fitted with a high resolution CTD and bio-optics package and an Autonomous Profiling Nutrient Analyzer (APNA). A photograph is shown in Figure 1. The APNA is a multi-channel nutrient analyzer that can be configured for simultaneous real-time profiling of up to four dissolved nutrients. The goal was to deploy the IOPC Profiler with APNA for up to one month during the 2005 and 2006 LOCO field expeditions. The chemical analyzers on the array were serviced as required during the multi-week efforts. Nutrient profile data was telemetered in real-time (post profile) from the IOPC profiler, shared with the other PIs and used to guide ship-based sampling. Time series data from this profiler, embedded within the larger ORCAS array, will allow us to quantify the temporal and vertical spatial scale, and variability, of steep nutrient gradients and plumes and define their critical role for thin plankton layer formation, maintenance and dissipation at a coastal site.

2. **SubChemPak Analyzer deployed on URIs slow-drop vertical profiler.** Periodic shipboard vertical deployments (with horizontal station spacing) of a SubChemPak Analyzer (several nutrients) on URIs (Donaghay) slow-drop vertical profiling package. This profiler comprised of URI’s (Donaghay) high resolution CTD/bio-optics package and one of our multi-channel SubChemPak Analyzers (see Hi-Res Profiler photo in Figure 1) was deployed periodically from a small boat. The SubChemPak Analyzer was configured for simultaneous real-time profiling of up to seven dissolved nutrients (nitrate, nitrite, phosphate, silicate, ammonium and iron(II) and iron(III)). A separate boat-deployed vertical profiling package with a water sampling system (Donaghay and Rines) was also used for the rapid collection of water samples from multiple discrete depths, with ~20 cm scale resolution. These comparative water samples were analyzed for nutrients and used to validate the analytical accuracy and vertical depth resolution of the IOPC-APNA, ship and AUV deployed SubChem Analyzers. The periodic vertical deployments of the slow-drop sensor package (with horizontal station spacing) allowed us to verify some of the high-resolution concentration data generated by the IOPC-APNA and obtain additional vertical and limited horizontal concentration data on the full suite of nutrients within the vicinity of the ORCAS array.

3. **Deployment of the URI REMUS vehicle with the MARCHEM Analyzer**, to map (3-D) multiple chemical, physical and bio-optical properties with high resolution (target 10-20 cm vertical, 1-2 m horizontal). The REMUS is an excellent platform for high-resolution 3-D mapping of the horizontal and vertical variability of nutrients and other chemical, physical and optical parameters in coastal waters. The MARCHEM for REMUS was configured to measure ammonia. The URI REMUS is also equipped with upward and downward looking ADCP, CTD, and sensors for oxygen, chlorophyll fluorescence, and particle scattering. In addition to quantifying the spatial coherence of thin layers and associated nutrient gradients between profilers, the 3-D nutrient mapping capability would also be useful for addressing specific scientific opportunities that may arise, like tracking and mapping significant nutrient plumes or gradients to their source.

WORK COMPLETED

Data processing and analysis from LOCO 2005 and 2006 Field Expeditions in Monterey Bay, CA: During the past year we calculated and processed all of the nutrient data that was obtained during the two annual LOCO field experiments that were conducted in Monterey Bay, CA. A custom MATLAB toolbox had been developed and was used to calculate and plot the analytical results from multiple profiles that were collected during the two annual field programs. This software toolbox was particularly useful for calculating the results for the 200+ profiles collected during the two-week field deployment of APNA II on the ORCAS IOPC Profiler in Monterey Bay during 2006. The nutrient data sets that have been collected are summarized in Table 2.

Table 2. Summary of LOCO Nutrient Data Sets from 2005 and 2006 Field Expeditions.

Nutrient Data Type	**8/12/05 to 9/2/05**	**7/13/06 to 7/26/06**
IOPC-APNA hourly profiles	~7	~240
Hi-Res Ship-board profiles	~35	~40
MARCHEM-REMUS Survey	3 – 1 hr missions	1 - 4hr mission
Nutrient Samples- nearshore	~75	~50
Nutrient Samples- offshore	~85	~100

The final stage of nutrient data processing involves careful evaluation and verification of the analytical calibration and the quality and consistency of the complete nutrient data set. We are utilizing three independent and comparative methods to calibrate and verify the data obtained with the *in situ* nutrient analyzers during the LOCO field exercises:

1. Pre- and post-deployment bench-top calibrations with a series of prepared standards.
2. *In situ* standard-addition calibration check (near surface/at depth) as part of profile.
3. Intercomparison with “independent” nutrient results obtained on stored-frozen water samples collected from comparable discrete depths (density surfaces) in the water column.

RESULTS

We have utilized both cabled and autonomous submersible chemical analyzers for monitoring nutrient gradients associated with thin plankton layers during two field experiments (FY05 and FY06) in Monterey Bay CA. The nutrient data collected has given us some scientifically interesting evidence for the important role of steep nutrient gradients for the formation of thin plankton layers in coastal waters. These observations are summarized below.

Summary of nutrient results for the LOCO 2005 Field Experiment:

- Nutrients low in surface waters and increased sharply with depth, to the highest levels in near bottom waters (~ 20 meters).
- Near surface waters became increasingly nutrient depleted and the depth range of the nutricline gradually deepened with time during the study period.
- The phytplankton layers were often located near the surface during the day time – in waters with depleted nutrients. Distinct mid-depth thin plankton layers formed within the deep nutricline at night.

- From LOCO biologists (Donaghay, Rines, and Sullivan) the phytoplankton population was often dominated by dinoflaggelates, exhibited a diel migration behavior during LOCO 2005. The phytoplankton were located near the surface during the day time and apparently migrating into the nutricline at night and forming distinct mid-depth thin layers within the nutricline at night.

Summary of nutrient results for the LOCO 2006 Field Experiment: The nutrient data collected during the second LOCO field experiment in Monterey Bay (July-August 2006) also harbors some scientifically interesting results.

- During the earlier phase of the 2006 experiment (7/15/06) the nitrate, ammonia, phosphate and silicate were present at relatively high concentration levels throughout the water column, which would explain, among other things, the presence of much healthier diatoms (pers. comm. J. Rines).
- By 7/21/06 depletion of nutrients was observed in the upper portion of the water column (0 to ~6 meters). Within and below the thermocline the concentrations of nutrients gradually increased with depth with the highest levels in near bottom waters as shown in Figure 2.
- The distribution of nitrate in the later part of July 2006 seemed to be similar to the distributions seen in August the year before and there was again some evidence for thin layer formation at depth due to migrating phytoplankton (pers. comm.. P. Donaghay).
- From this data, the vertical flux of nitrate ($NO_3 + NO_2$) was calculated using a simplified eddy diffusion model – Flux = $K_Z(\Delta NOx/\Delta Z)$. Vertical nitrate flux distributions were then compared with vertical [chlorophyll a] distributions – during daytime and night-time conditions – in order to elucidate the impact of nutrients on phytoplankton, as well as, of phytoplankton on nutrients (Figure 3).

IMPACT/APPLICATIONS

The field research phase of this project has given us the opportunity to continue to improve our autonomous and ship-board chemical profiling technologies and allowed us to continue our investigations of the effect of nutrient gradients and plumes on thin plankton layer dynamics. We have obtained important data on how fine-scale chemical gradients and nutrient plumes may vary in an open coastal system and influence plankton patchiness. As we further interpret the large volume of nutrient data collected we expect that we will be able to contribute towards the development of a predictive model for the role of nutrients in thin plankton layer formation and productivity in coastal waters.

The LOCO project has also given us the opportunity to demonstrate some emerging autonomous chemical profiling technologies within the matrix of a scientific experiment. The successful deployments of the APNA on the IOPC profiler and the MARCHEM analyzer on the REMUS vehicle both represent substantial advancements in the development of this technology and bring us much closer to a demonstrated capability for sustained, autonomous ocean observations of nutrient distributions and variability.

TRANSITIONS

The APNA instrumentation is now commercially available from SubChem Systems, Inc and WET Labs, Inc. Eight units were purchased and delivered to government and university laboratories in the USA, China and South Africa. The MARCHEM AUV nutrient sensing payload is slated for integration into HYDROID's REMUS-600 as part of the coastal component of the NSF Ocean Observatories Initiative. A contract is also in place with the Naval Research Laboratory (NRL) to adapt the MARCHEM AUV payload to utilize NRL immunosensor technology for the underwater detection of

explosives and other chemicals of interest that may be detected by the successful NRL analytical technology.

SubChem Systems and NRL have been granted a new FY08 NOPP award "Developing ChemFin, a Miniature Biogeochemical Sensor Payload for Gliders, Profilers, and other AUVs". WET Labs, Inc., SubChem Systems, Inc. and other partners have also been granted a new FY08 NOPP award "Long-term in situ chemical sensors for monitoring nutrients: phosphate sensor commercialization and ammonium sensor development".

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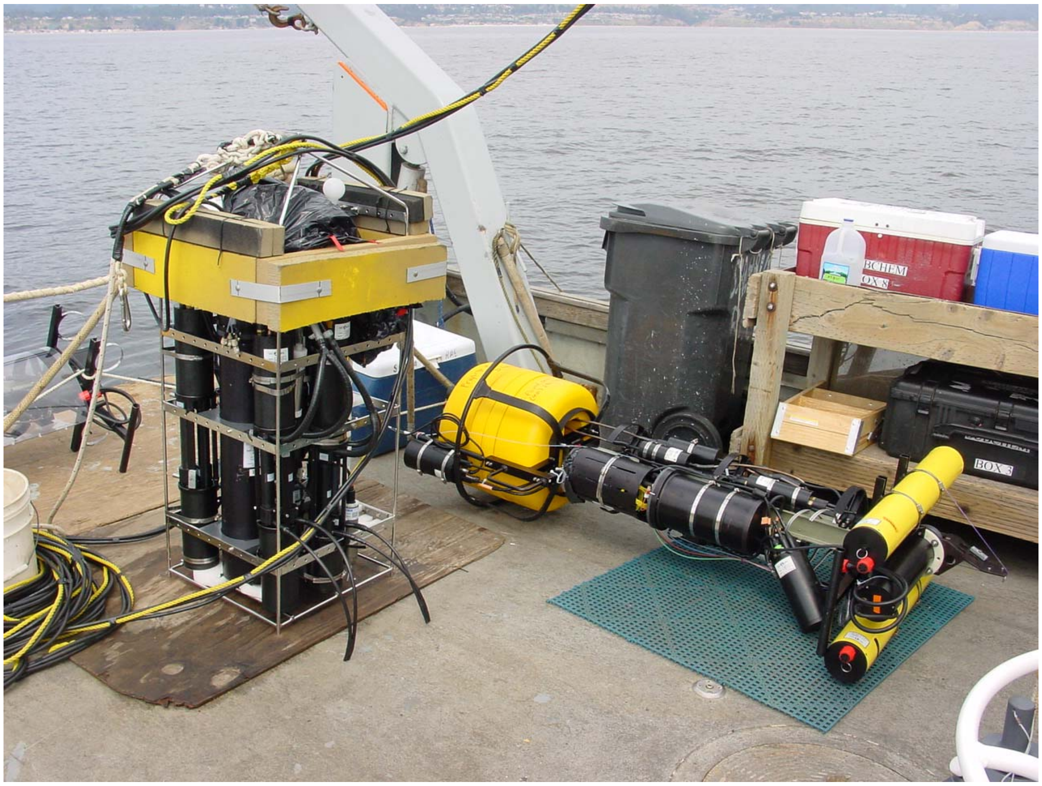

Figure 1.The autonomous URI IOPC profiler (on the right) with the APNA II nutrient analyzer payload and the URI High Resolution Profiler (on the left), with a SubChemPak Analyzer payload. [The URI High Resolution Profiler is a cabled, ship-deployed instrument that uses buoyancy adjustment to descend slowly through the water column while it measures a variety of physical, biological, optical and chemical properties of the water. The URI IOPC profiler is an autonomous, battery operated moored-profiler that may be deployed in the coastal ocean for weeks at a time. It contains a full suite of instruments and sensors for monitoring the physical, optical, biological and chemical properties of the water. The profiler can be programmed to make repeated profiles, from the bottom to the surface, on a pre-set time schedule, to send the results by radio telemetry to a shore- or ship-based receiver station, and then return to the bottom to wait for the time to start the next profile.]

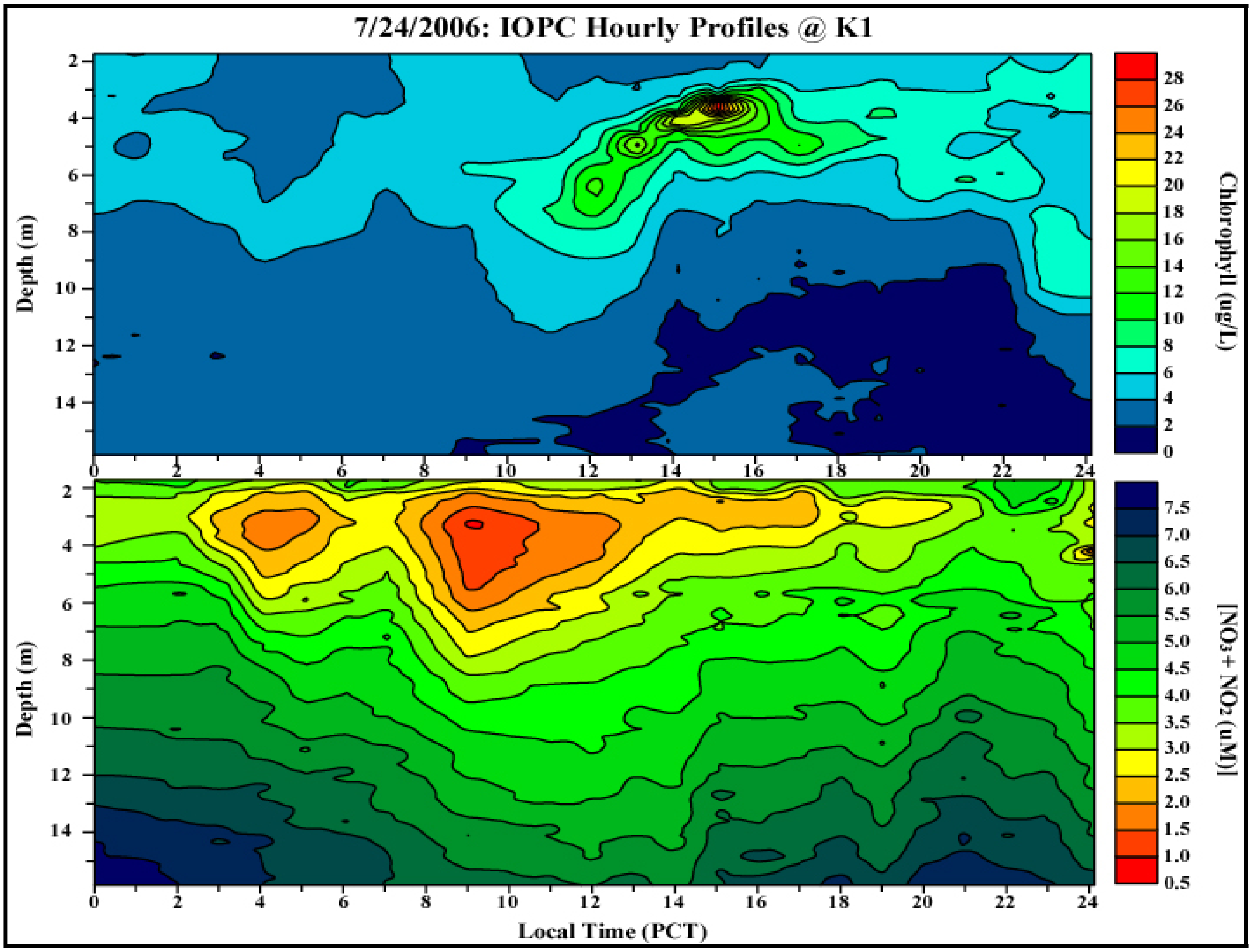

Figure 2. A times series of two graphs containing environmental data from 24 hourly profiles showing the dramatic temporal changes observed in the chlorophyll layers and vertical distributions of dissolved nitrate concentration and gradients in Monterey Bay for a 24 hour time period (Julian Day 205) during the LOCO 2006 field program.
[Note the mid-day near surface depletion of nitrate (red) and subsequent thin chlorophyll layer formation (green-red) coincident with the nitricline. This time series of profiler data was collected autonomously in real-time with the ORCAS IOPC profiler with APNA.]

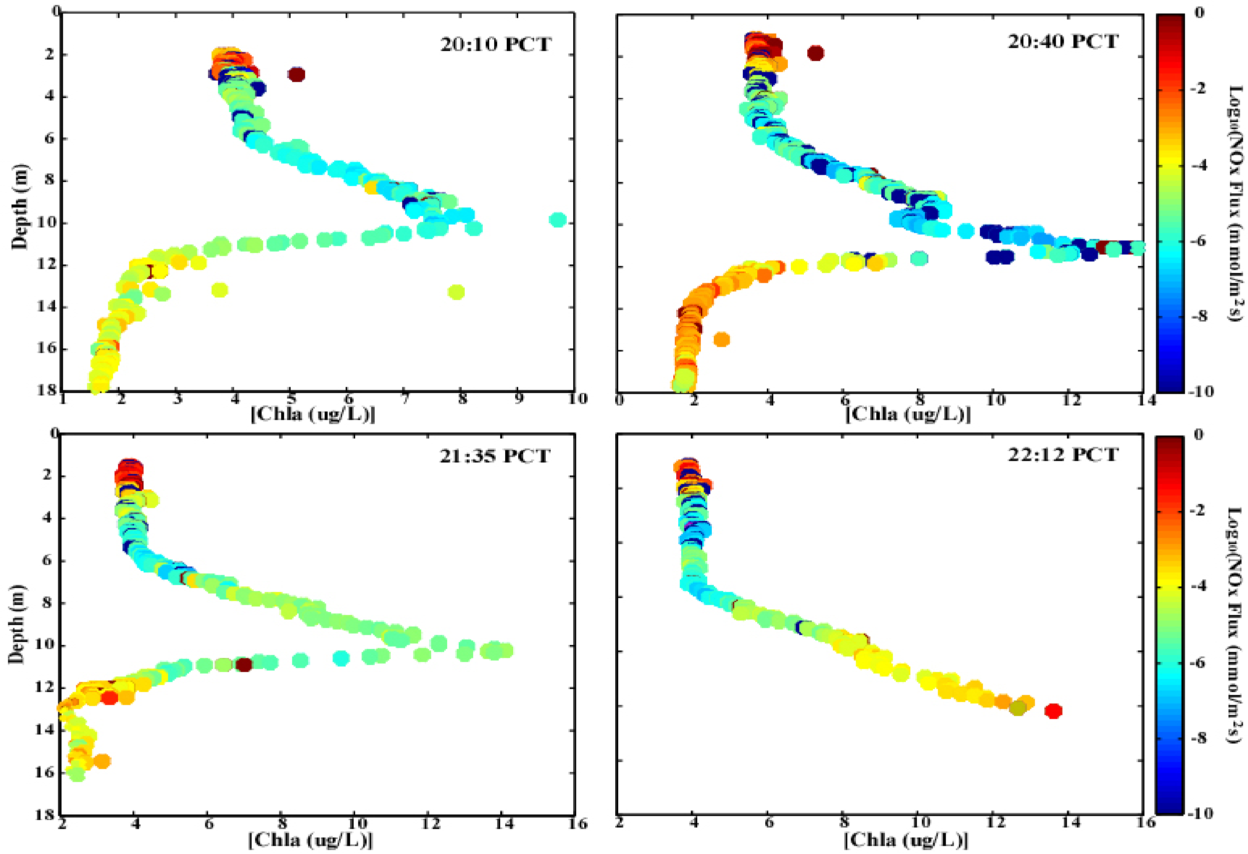

Figure 3. Four graphs representing a one hour times-series showing the relationship between the night-time, downward migration of motile phytoplankton (chlorophyll) and the vertical nitrate flux (color scale) calculated from the nitrate concentration gradients. The motile phytoplankton were observed to migrate downwards into waters with the highest nitrate flux, and no deeper.